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Thickness and Reinforcement Fiber Content Control in Composites by Vacuum-Assisted Resin Transfer Molding Fabrication Processes

by William A. Spurgeon

ARL-TR-3526 **June 2005**

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*
June 2005

2. REPORT TYPE
Final

3. DATES COVERED (From - To)
June 1999–September 2004

4. TITLE AND SUBTITLE
Thickness and Reinforcement Fiber Content Control in Composites by Vacuum-Assisted Resin Transfer Molding Fabrication Processes

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
William A. Spurgeon

5d. PROJECT NUMBER
622618AH80

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
ATTN: AMSRD-ARL-WM-MC
Aberdeen Proving Ground, MD 21005-5066

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-3526

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This report presents two new vacuum-assisted resin transfer molding processes for fabricating polymer resin matrix composites. The processes enable the fabricator to control the volume percentage of reinforcement fiber from about 35% to 60%, depending on the weave style of the reinforcement. Control of the reinforcement content results in control of the thickness of the composite. The composites fabricated using these processes are also more uniform in fiber distribution than similar composites processed by previously available techniques.

15. SUBJECT TERMS
vacuum-assisted resin transfer molding, thickness, and volume fraction control

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL	38	William A. Spurgeon
					19b. TELEPHONE NUMBER (*Include area code*) 410-306-0768

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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1. Introduction

This report describes new vacuum-assisted resin transfer molding (VARTM) polymer matrix composite fabrication processes developed at the U.S. Army Research Laboratory (ARL). The processes were developed in response to the perceived need to be able to control the thickness and reinforcement fiber volume fraction (V_f) of composites for a variety of applications. Conventional VARTM processes such as Seeman's Composite Resin Infusion Molding Process[1] (SCRIMP) do not offer adequate control of these parameters. Moreover, SCRIMP frequently results in composites with fiber content gradients. A brief discussion of SCRIMP as practiced at ARL is presented in the appendix.

The first of the new processes, described in section 2 of this report, is known as "Vmin"[2] since it was developed as a variation on SCRIMP that allows composites with relatively low values of fiber volume fraction (typically under 50 volume % glass) to be made. The desire for such a process arose during an effort to fabricate a large number of polyurethane resin based panels with low fiber content for high flexibility. The panels were made by hand, which required many precautions, and resulted in a product with large variations in thickness and general quality.

More generally, it is desirable to have a composite fabrication process that uses low cost tooling that allows the processor to:

1. control fiber volume percentage from 35% to 60%,
2. control the thickness of the part,
3. obtain good uniformity through the thickness of the part,
4. process large area parts rapidly,
5. process with viscous or very fast curing resins,
6. obtain a good surface finish,
7. generate a minimum of waste, and
8. turn off the vacuum system and walk away when the part is filled, with no circulation of resin through the part or removal of resin required.

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[1] Seeman, W. H. *Plastic Transfer Molding Techniques for the Production of Fiber Reinforced Plastic Structures*, U.S. Patent No. 4,902,215, 20 February 1990.

[2] Rigas, E.; Spurgeon, W. A.; Walsh, S. *Fabrication of Composite Skirts for Tracked Vehicles Using FASTRAC Processing Techniques*; ARL-TR-2868; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2002.

A detailed analysis of SCRIMP pointed the way to a process that meets these objectives. This new process, volume control VARTM, is described in section 3 of this report.

2. Vmin

2.1 Background

Composites made by standard vacuum bag methods, using typical reinforcement fabrics and either wet resin lay-ups or prepreg technology, will usually contain about 50% fiber by volume. These vacuum bag methods are not satisfactory for making a composite with a lower volume fraction of reinforcement fiber. However, ARL experience has shown that adding a large excess of resin to a wet resin or prepreg lay-up generally results in a poor quality part that is hard to reproduce and that typically has a high void content. Some control over the fiber volume fraction can be obtained by using a fabric with a different weave pattern such as a 0–90-stitched fabric or a chopped strand mat as opposed to a plain weave fabric. It is not always possible or desirable to change fabric style, however.

VARTM or variations on this process, such as SCRIMP, result in a fiber volume fraction determined by the applied pressure and the weave of the fabric. The degree of control over the fiber volume and part thickness obtained by methods that do not use a mold is minimal, however. Resin transfer molding is often an alternative to vacuum bag methods. The volume fraction of fiber in a composite part made by this method can be controlled by the amount of compression the mold provides to the dry fabric. The mold also determines the part thickness. However, this process requires a relatively expensive closed mold, which could be an unacceptable expense if only a few parts are needed. If composites with a low volume fraction of reinforcement fiber are needed, a simple, reliable method of fabricating them is clearly desirable.

2.2 The Vmin Process

Vmin employs VARTM or variations on this process, such as SCRIMP, to fill the part with resin. For a flat panel, the reinforcement fabrics are first cut slightly (typically 0.5 to 1 in) larger than the desired part size. Referring to figure 1, the desired number of plies of cut fabrics (2) are then stacked on a rigid bottom plate (1), which is typically metal. Rigid supports (or spacers) (3), also typically metal, are placed along two opposite sides of the fabric stack. One or more plies of a porous release fabric (hidden under item 4) and a layer of distribution medium (4), cut no larger than the fabrics, may then be placed on top of the fabric stack, as in SCRIMP. A fill line (5) is placed on one of the unsupported sides and a suitable vacuum line (6) is placed on the other. A rigid cover plate (not shown), typically metal, that is wider than the fabrics and just slightly longer is then placed over the assembly so that it rests on the rigid supports. Following standard practice, the assembly is then vacuum bagged, evacuated, and infused with resin that is then cured. Finally, the part is debagged and trimmed to size.

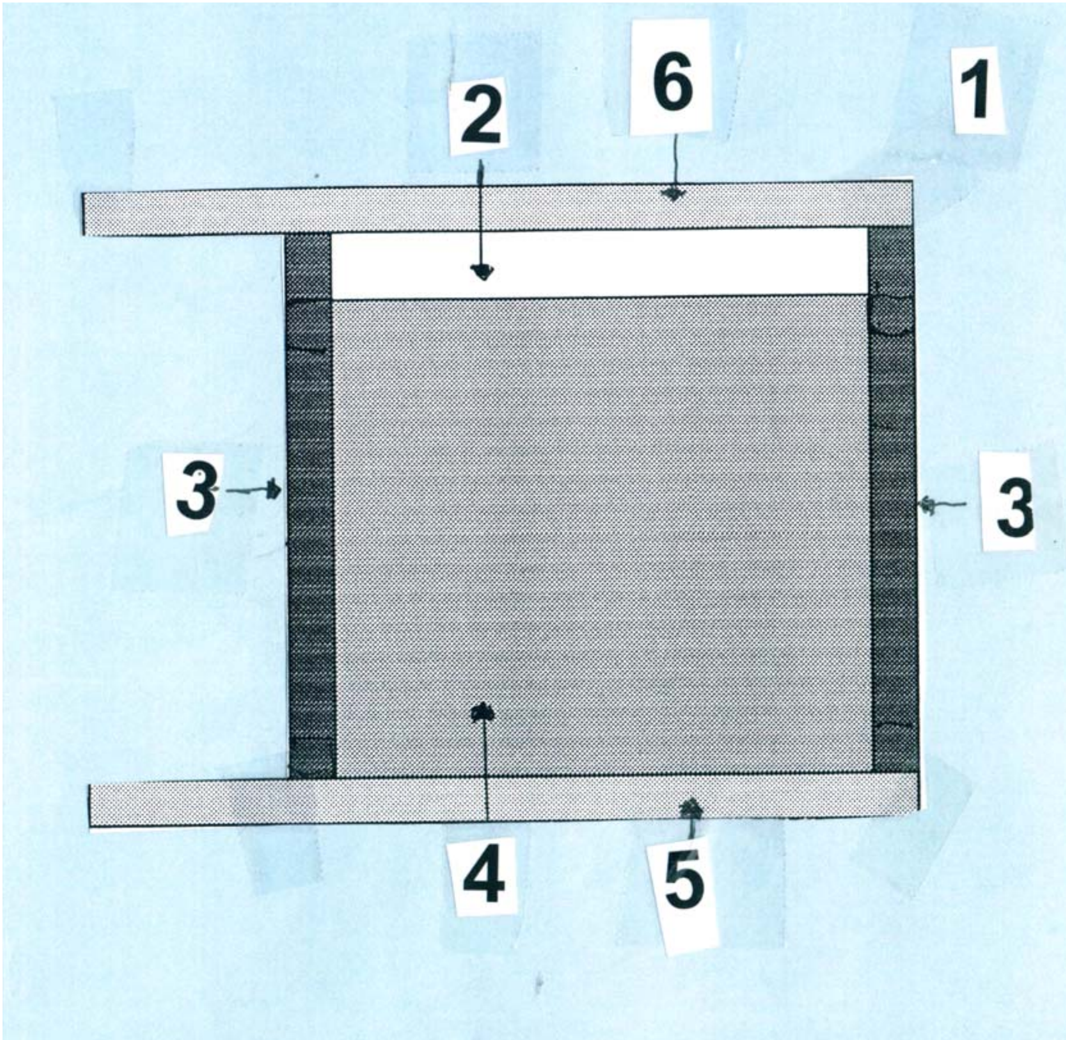

Figure 1. A top view of the first setup for fabricating a composite part with a low volume percentage of reinforcement fibers. Legend: 1-rigid base plate, 2-cut fabrics, 3-rigid spacers, 4-release fabric and transfer medium, 5-fill line, and 6-vacuum line.

Invariably, a small space or gap is left between the cut fabric stack (2) and the rigid supports (3) in figure 1. It is possible for resin to flow preferentially through this space to the vacuum side instead of flowing through the fabric stack, a process known as “racetracking.” Since the resulting part is not completely filled with resin, it is not the desired product. It is thus important that this space be minimized, or that the racetracking be otherwise prevented. It is possible to avoid this racetracking altogether by cutting the fabrics to a particular pattern and supporting the cover plate in a slightly different manner. For a flat panel, the fabrics are first cut as shown in figure 2. The central square region in the figure represents the intended size of the final part. Referring to figures 3 and 4, the desired number of plies of cut fabrics (1) are then stacked on

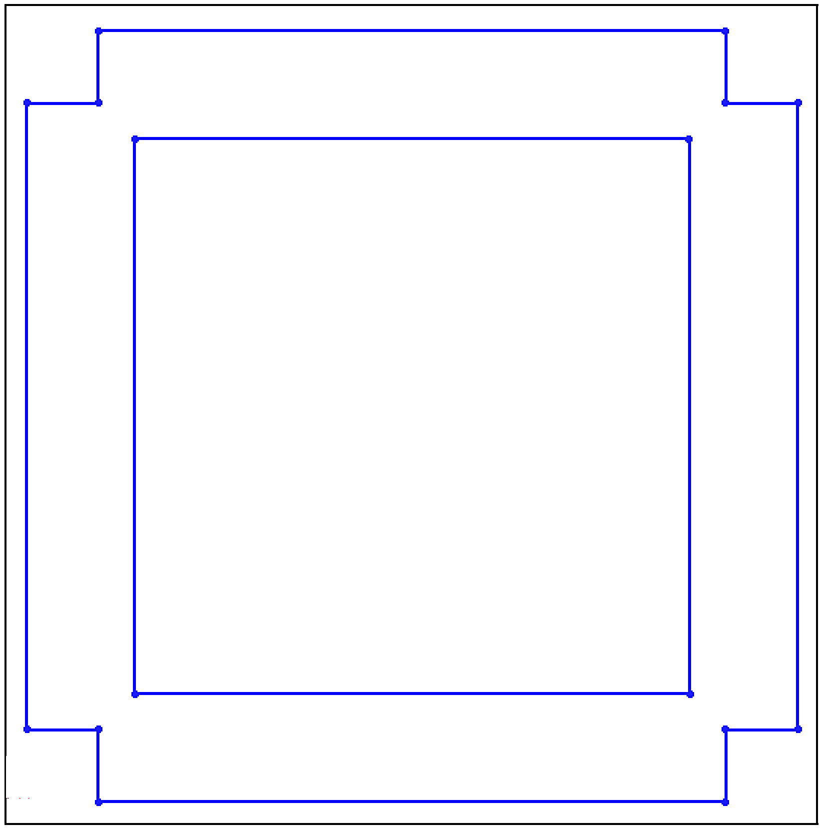

Figure 2. The basic pattern for cutting the fabrics for fabricating a composite part by the setup in figures 3 and 4. The intended part size is that of the inner box.

a rigid bottom plate (7). The fabrics are typically 2 in larger on each side than the desired part size. The notches in the fabric are typically 1.5 in deep and 1 in wide. These notches will hold rigid supports (3) (typically metal) that will support a rigid cover plate (4) (also typically metal). Rigid support spacers (3) that will determine the thickness of the panel are placed in the notches on in the fabric plies. A rigid cover plate (4) is placed over the spacers for simple vacuum resin transfer molding. One or more layers of a porous release material (not shown), cut to the pattern of figure 2 could be placed over the fabrics if desired, for example, to give the upper surface a slight texture to enhance paint adhesion. Alternatively, for a SCRIMP—like process, one or more layers of a porous release material cut to the pattern of figure 2 are first placed over the cut fabrics. A layer of an appropriate transfer medium material is placed over the release material.

This is cut to the size of the finished part plus a little extra on one side to join to the fill line, as shown in figures 3 and 4. A rigid cover plate (4) is then placed over the metal spacers. A resin fill-line (5) and a vacuum line (6) and are placed adjacent to the part as in figures 3 and 4, and the entire assembly is vacuum bagged. The bag should clamp down hard on the exposed fabric edges (the portions of the cut fabrics visible in the top view in figure 3) right up to the edge of

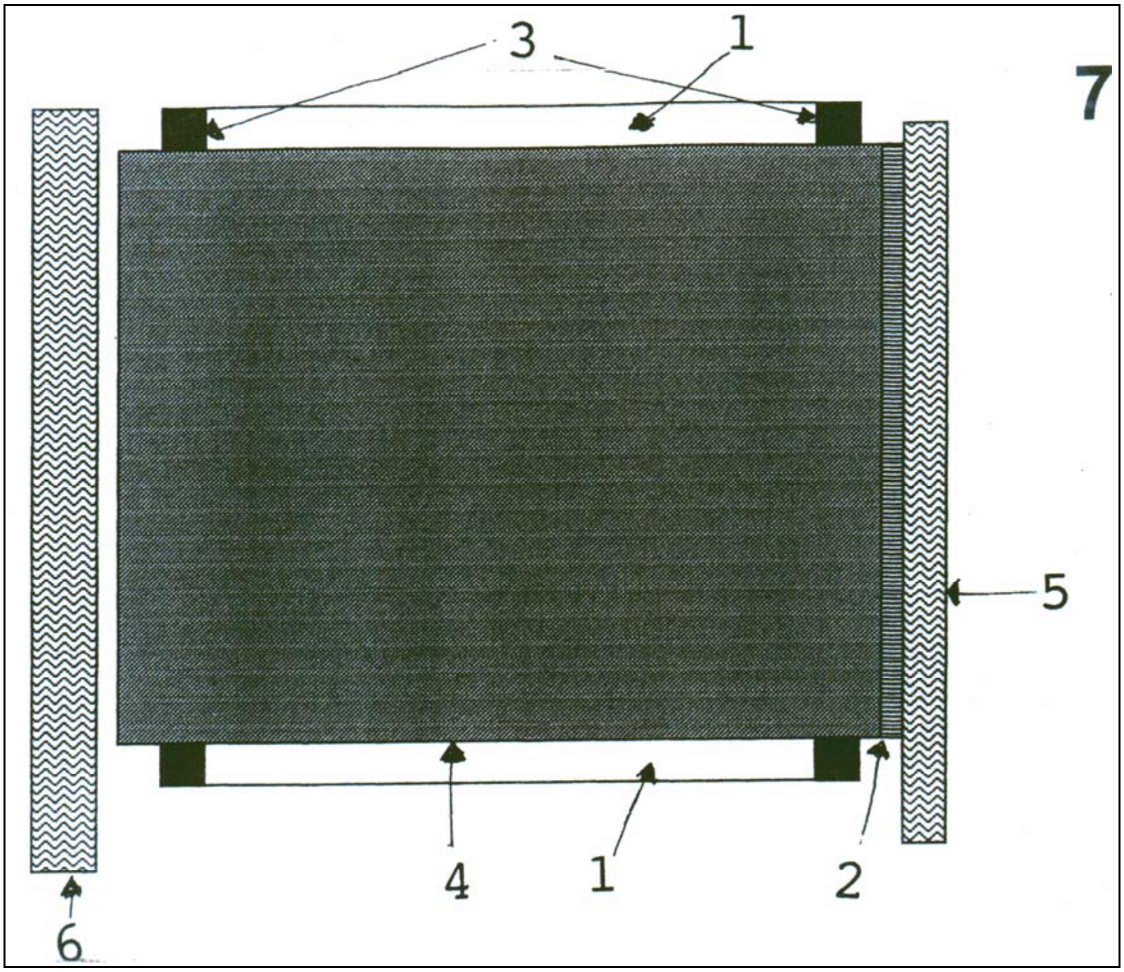

Figure 3. Top view of the second setup for fabricating a composite part with a low volume percentage of reinforcement fibers. Legend: 1-cut fabrics, 2-transfer medium over release fabrics, 3-rigid spacers, 4-rigid cover plate, 5-fill line, 6-vacuum line, and 7-rigid bottom plate.

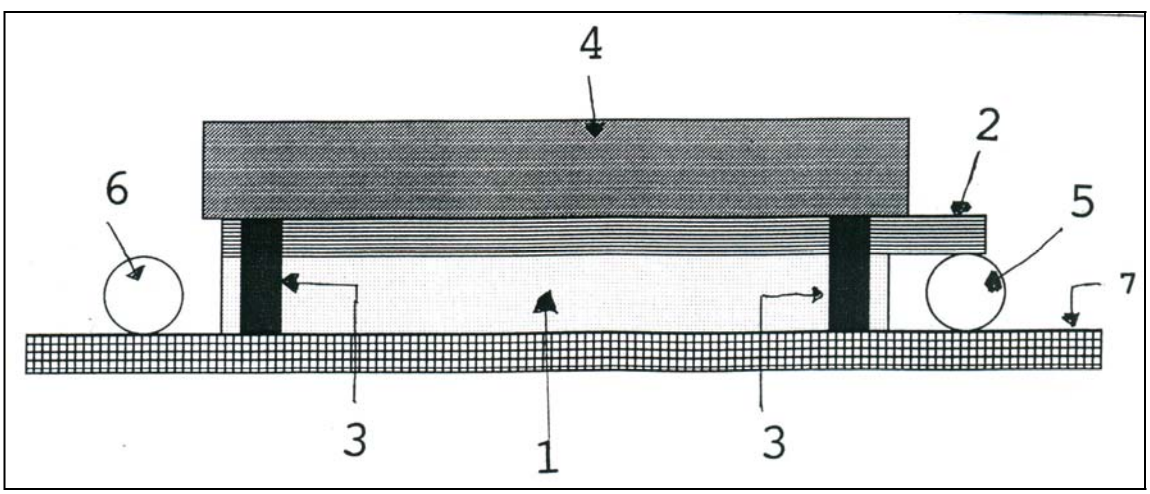

Figure 4. Side view of the second setup for fabricating a composite part with a low volume percentage of reinforcement fibers. Legend: 1-cut fabrics, 2-transfer medium over release fabrics, 3-rigid spacers, 4-rigid cover plate, 5-fill line, 6-vacuum line, and 7-rigid bottom plate.

the cover plate. This helps prevent racetracking of the resin and helps ensure a complete fill-out of the fabric. It is also necessary to stuff several strips of fabric into the exposed edges of the fabric stack at regular intervals. These strips are the size of the exposed edges and are inserted to prevent the vacuum from pushing down the fabric under the cover plate. The number of such strips required will vary with the part, but enough should be inserted so that the edges will be about as thick as the support spacers (3) when it is placed under vacuum. This also increases the impedance to flow at the edges of the part and thus helps eliminate racetracking. The bag is then evacuated and resin is infused into the part. The part is then cured, cooled if the resin required heat to set, debagged and trimmed to size, following standard practice**.**

Although the previous description is for a flat plate, it should be clear that a shaped part could also be made by this method. All that is needed are appropriately contoured rigid male and female top and bottom plates and some rigid spacers. A closed mold is not required.

For a large panel the new method is modified slightly as shown in figures 5 and 6. The reinforcement fabrics (1) and release fabric (4) are cut to the pattern in figure 7 and placed on the bottom plate (7). These fabrics will have as many slots for spacers as needed. The transfer medium (not shown) is cut 1/2 in to 1 in smaller than the part on all sides and placed over the release fabrics. The cover plate (4) is in two sections (or more if the part is very large). Support spacers (3) are placed in the notches in the fabric stack. The fill line (5) is placed over the space between sections in the cover plates (4). The vacuum lines (6) are placed at the edges of the panel. Extra strips of fabric are placed within the exposed edges of the stack of cut fabrics. The part is then vacuum bagged and infused with resin that is then cured. Finally, the part is debagged and trimmed to size.

With fabrics such as a 24-oz 5 × 5 woven roving, fiber volume percentages from ~37% to 50% were obtained by this method. Attempts to make lower volume fraction composites with this fabric resulted in composites with unacceptably high concentrations of voids. Lower volume percentage composites require the use of a chopped strand mat or other high bulk factor reinforcements or preforms.

2.3 Examples

A number of samples were fabricated using the Vmin process in order to demonstrate reduction to practice. In the first example, six plies of 24-oz per square yard 5 × 5 S-2 glass woven roving ~16-in square were cut in the pattern of figure 2. Aluminum support spacers, each 0.25 in thick, were placed in each of the four notches in the fabric. Two plies of Richmond Products type A-8888 release fabric* were cut to the pattern of figure 2 and placed over the fabrics. A layer of 50% shade awning mesh† was then placed on top of the stack to serve as a distribution medium.

*Northern Fiberglass Sales, Inc., P.O. Box 2010, Hampton, NH 03843-0598.

†Roxford Fordell, 16 Pelham Davis Circle, Greenville, SC 29615.

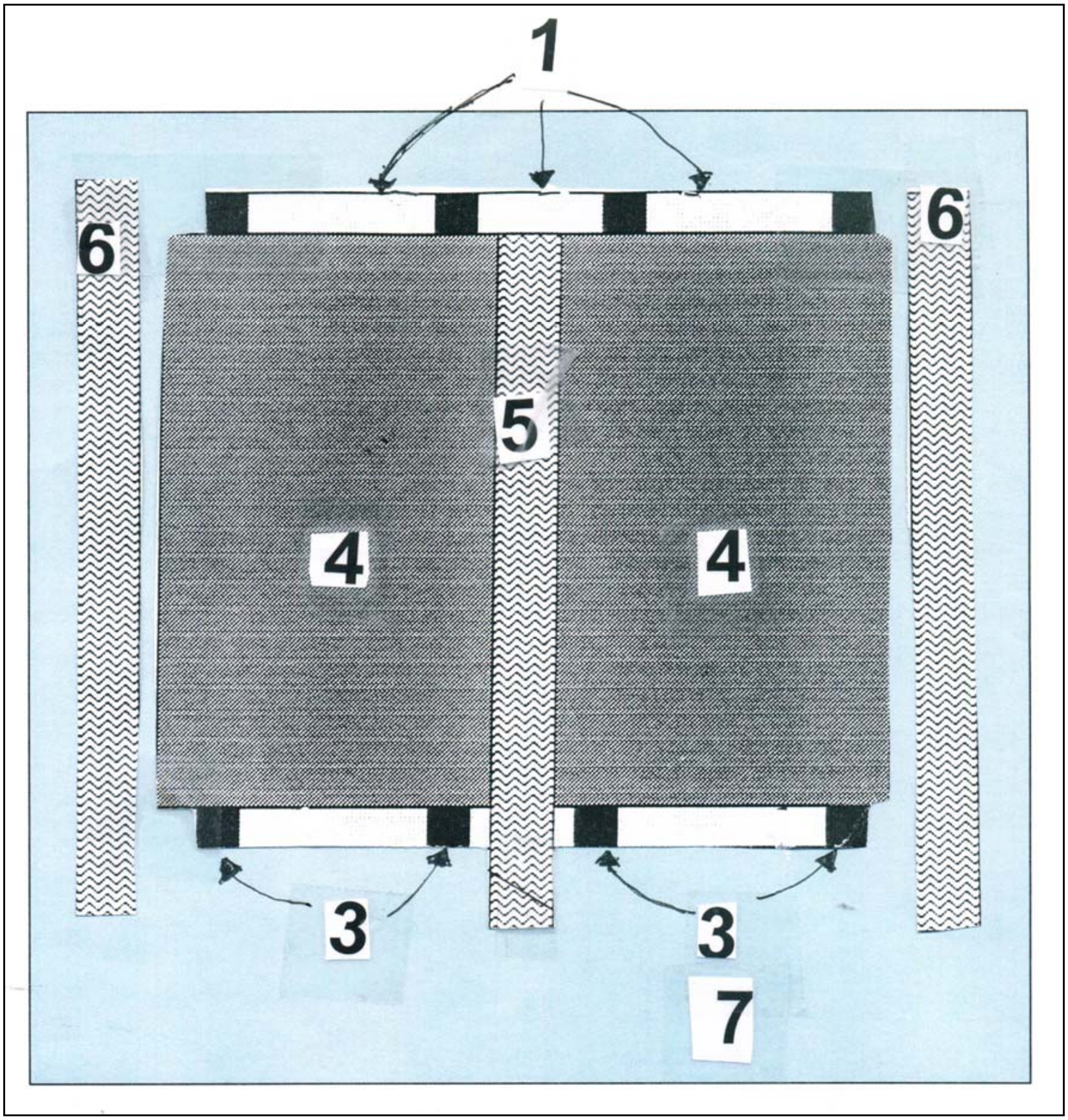

Figure 5. Top view of a modification of the setup in figures 3 and 4 for fabricating a large composite part with a low volume percentage of reinforcement fibers. Legend: 1-cut fabrics, 2-release fabrics, 3-rigid spacers, 4-rigid cover plate, 5-fill line, 6-vacuum line, and 7-rigid bottom plate.

It was cut to the size of the final part and plus one inch on the one side that abutted the fill line. This was then covered with a 13-in square, 0.625-in thick aluminum cover plate that rested on the four 0.25-in thick aluminum support spacers. Two strips of the woven roving were placed within the exposed edges of the stack and two more of the woven roving strips were placed over the top of the edges. A fill line was made by taking a 12-in piece of 0.5-in inner diameter polyethylene spiral electrical wire wrap* that had been stretched to a length of 16 in. This was

*Panduit Type T62F, obtained from Graybar Electric, 43 Boulden Blvd., P.O. Box 900, New Castle, DE 19720.

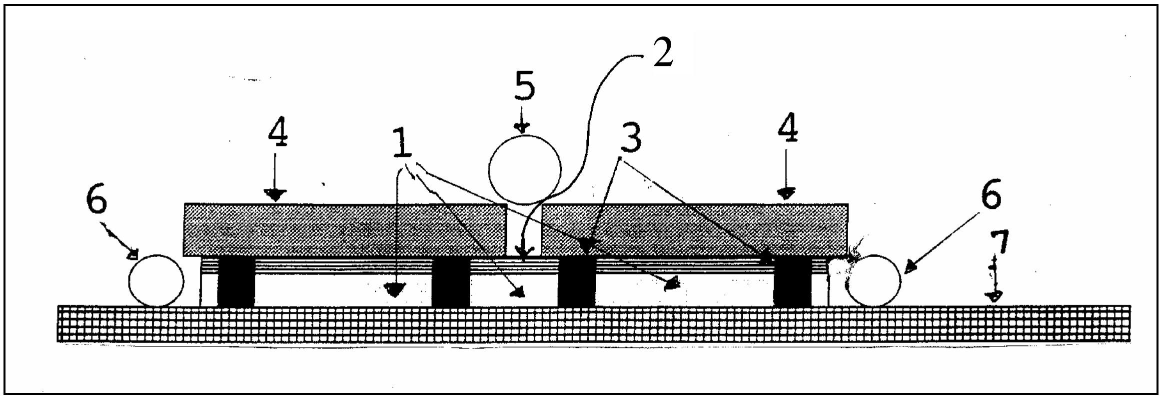

Figure 6. Side view of a modification of the setup in figures 3 and 4 for fabricating a large composite part with a low volume percentage of reinforcement fibers. Legend: 1-cut fabrics, 2-release fabrics, 3-rigid spacers, 4-rigid cover plate, 5-fill line, 6-vacuum line, and 7-rigid bottom plate.

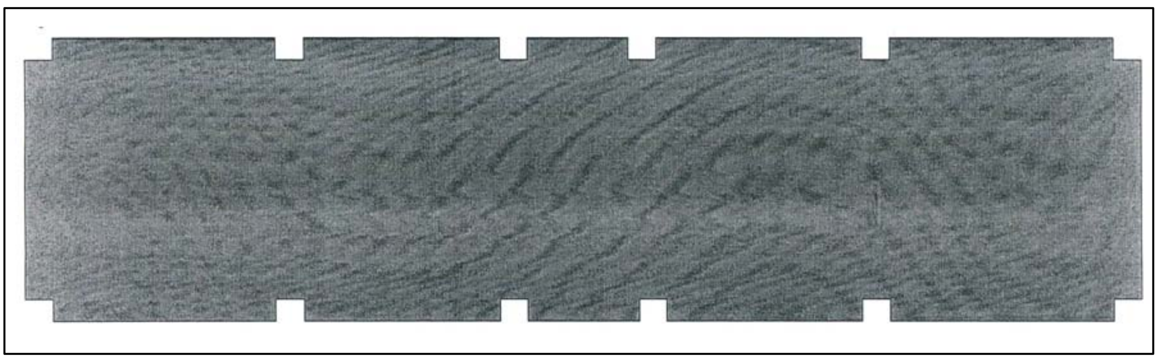

Figure 7. The basic pattern for cutting the fabrics for fabricating a large composite part by the setup in figure 5. Cut-outs for four additional spacers are shown.

then wrapped with several layers of the 50% shade awning mesh material. One inch of the spiral wrap was wrapped around a piece of 0.5-in OD by 0.375-in ID polyethylene tubing at the end nearest the resin source. A similar piece of spiral electrical wire wrap was wrapped with several layers of type 7781 E-glass fabric and joined to a piece of polyethylene tubing for a vacuum line. The fill and vacuum lines were put in place and the assembly was then vacuum bagged and infused with polyester resin* and cured. After the part had cooled, the edges were trimmed, leaving a 12-in square composite plate 0.197 in thick, and had a fiber volume percentage of 38.4% ± 0.6% (0.033 in/ply).

A part made by conventional SCRIMP using 10 plies of the fabric was 0.249 in thick and had a fiber volume percentage of 50.6% ± 0.15% (0.0249 in/ply).

Figure 8 shows the various materials used in the process—the A8888 release fabric (1), 40% shade awning mesh (2), vacuum line (3), composed of polyethylene tubing and glass fabric covered electrical spiral wrap, a fill line (4) composed of the polyethylene tubing and spiral wrap, and vacuum bagging material (5).

*Type E-701, Alpha Owens - Corning, Valparaiso, IN.

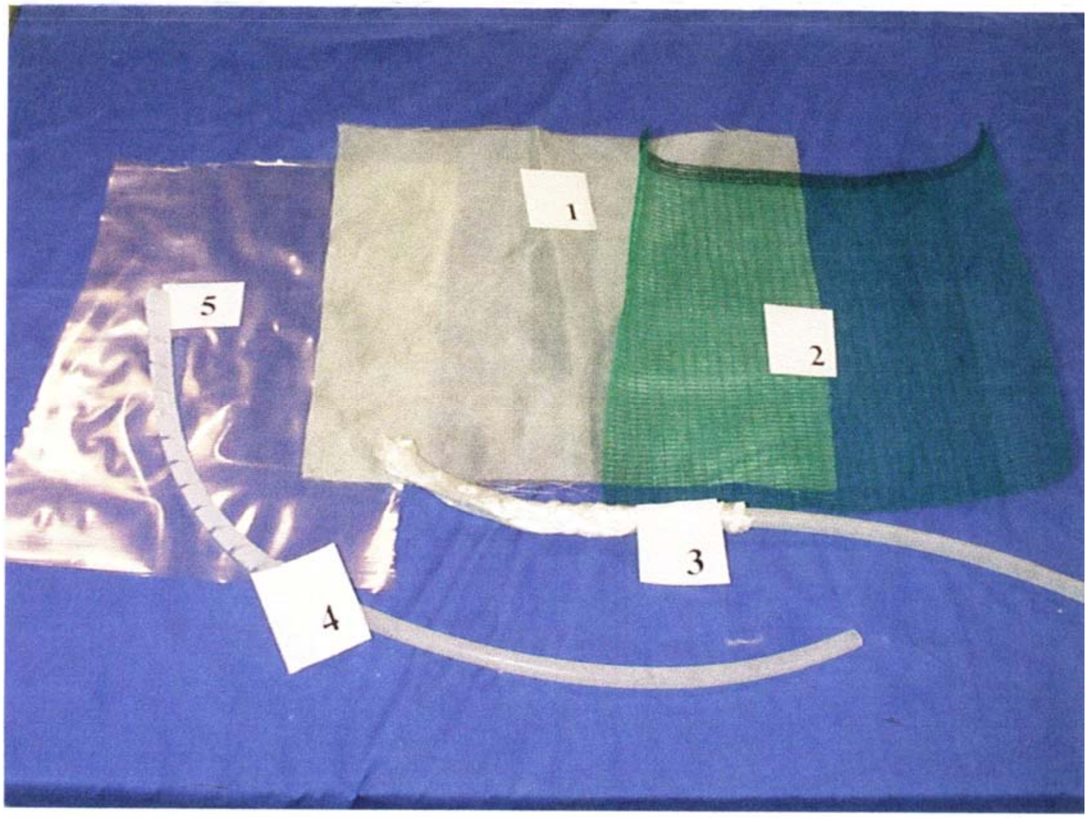

Figure 8. The materials used in the V-min process: (1) A8888 release fabric, (2) 40% shade awning mesh, (3) vacuum line, (4) composed of polyethylene tubing and glass fabric covered electrical spiral wrap, a fill line, and (5) composed of the polyethylene tubing and spiral wrap, and vacuum bagging material.

In a second example, 15 plies of 8.8-oz per square yard style 6781 S-2 glass fabrics were cut to the pattern of figure 2. As in figures 3 and 4, the cut fabric plies were covered with release fabrics, distribution medium, and an aluminum cover plate supported by four 0.25-in thick aluminum spacers. Ten additional strips of cut type 6781 fabric were stuffed at regular intervals into the exposed edges of the fabric. Fill and vacuum lines were put in place and the assembly was vacuum bagged, infused with polyester resin, cured and debagged as in the previous example. The resulting part had a glass content of 36.4 ± 0.2%. An identical panel was also made from 15 plies of the same glass fabric by the method in figure 1. The parts were translucent, indicating a low void content. Samples prepared by SCRIMP typically had 44% ± 1% glass by volume.

In a third example, 15 plies of the type 6781 S-2 glass fabric were cut 11.5-in square and stacked as in figure 1. The plies were then covered with the release fabric and distribution medium. Two aluminum support spacers, 0.25 in thick × 2 in wide × 12 in long, were placed adjacent to the part. A 13-in square by 0.625-in thick cover plate was placed on top of the spacers. Fill and vacuum lines as in the previous examples were placed adjacent to the fabrics as in figure 1. The part was infused with a polyurethane resin, cured, cooled, and trimmed to size. It was found to contain 33.3% ± 0.2 % glass by volume, as expected.

In a fourth example, 4 plies of a chopped strand E-glass mat were cut as in figure 2, put in place, vacuum bagged and infused as in the two previous examples. It contained 30.0 ± 0.5 volume % glass. A 4-ply part made by conventional SCRIMP using this glass mat contained 41.9% ± 0.4% glass by volume.

All physical properties of composites that depend on the volume fraction of reinforcement fiber can be controlled by using the Vmin process. This includes electrical, mechanical, and thermal properties. The process also controls the thickness of the part through the use of spacers.

U.S. patent number 6,406,660, "Method for producing polymer matrix composites having a low volume percentage of reinforcement fiber and controlled thickness," was issued in June 2002.

3. Volume Control VARTM

A practical and reproducible method of fabricating a composite with a relatively low V_f was described in the previous section. However, a high V_f is more desirable in many applications. It is also desirable to have a composite in which V_f is uniform throughout the sample. In particular, the gradient in V_f from the top of the sample to the bottom that is often present in a panel fabricated by SCRIMP should be absent. These factors pointed to the need for a more general method of V_f control via an easy to implement VARTM process.

A feeler gauge with 0.001-in sensitivity was used to monitor the thickness of a part being made by SCRIMP with resin infused from one end. The thickness of the part, measured near the fill line, remained unchanged until the part had almost filled out. Although most of the part is generally filled out at this point, after the center of the part is done. The thickness of the part then started to increase as additional resin was added to finish filling the edges of the part farthest from the fill line. This indicated that stopping the infusion before the part was completely filled out would lead to a part with the maximum V_f obtainable using only one atmosphere of pressure on the part in a vacuum bag. Subsequent experiments established that this V_f was typically 0.59 and 0.60. It is also evident that the uniformity of the section of a composite panel that is infused this way will be as good as it can be and is limited by the uniformity of the plies of fabric used.

The rate of flow of resin into the part is limited by the distribution medium and the thickness of the part in SCRIMP. The resin must flow across the part as well as through the part. An alternative is to quickly distribute the resin across the surface of the part and allow it to soak through. This is the basis of another processing method known as FASTRACK. FASTRACK overfills the part during the process, which necessitates vacuuming off the excess resin. It also leaves a very nonuniform backside on the part. This nonuniformity is not acceptable in many applications.

In order to overcome these difficulties, the process shown schematically in figure 9 was developed. The cut fabrics are placed on a plate to which mold release had been applied, covered with a layer of release fabric (omitted in the figure), and two vacuum lines are placed on several plies of scrap fabric hat are abutted to the bottom of the part. The reusable processing apparatus is placed on top of the part as shown in the sketch. The assembly is vacuum bagged and the part is then infused with resin.

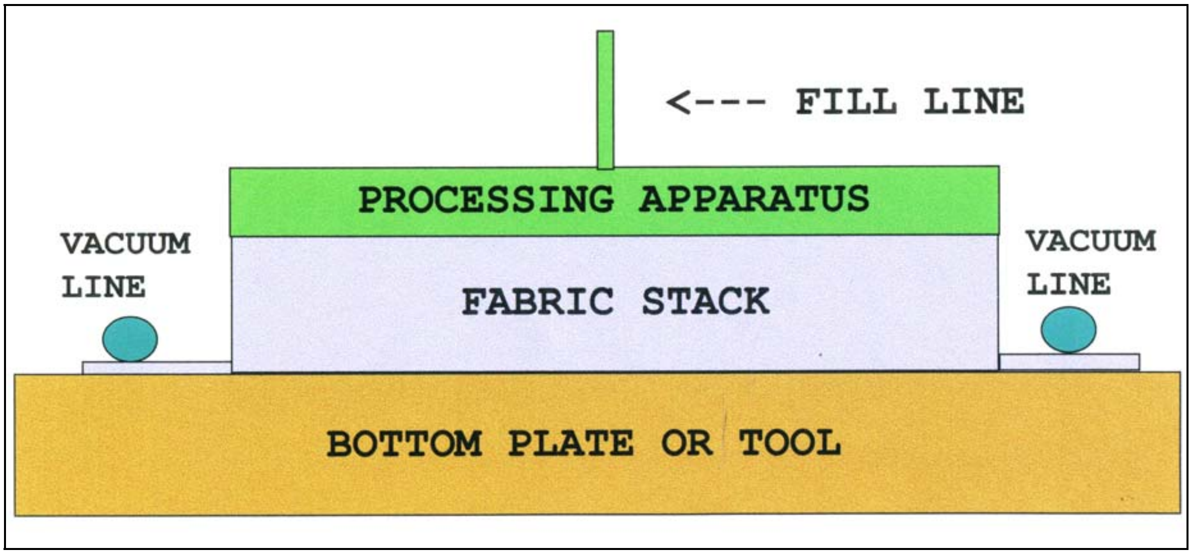

Figure 9. A sketch of the second new VARTM process.

Processing apparatus consisting of a top and a bottom plate is shown in figure 10. The top plate, at the left in the figure, has a hole in the center for resin input and a slot about 0.5 in wide and 0.125 in deep that stops ~0.5 in from the edge of the plate. The bottom plate at the right in the figure has a series of 0.0625-in slots milled as shown. These slots stop ~1 in from the sides of the part and 2 in from the ends (with the vacuum lines). The part with the wider slot is placed perpendicular to the other.

A vacuum bagged part ready for resin infusion is shown in figure 11. This processing method worked very well; all parts filled out rapidly without dry spots. The surface finish of the parts was excellent; the resin infusion slots left marks on the part that could be seen but not felt, even with soft and pliable type 7781 E-glass fabrics. It can be seen that the edges of the metal apparatus were covered with a blue tape. This prevents the edges of the metal apparatus from cutting through the vacuum bag.

No attempt was made to optimize the size of the slots because the fill rate was quite rapid for the parts that were fabricated. The speed was limited by the soak through time in all parts that were fabricated. One sample was made using a resin with sufficient catalyst to reduce the pot life to ~5 min. A very satisfactory 0.25-in thick part was also made using a polyurethane resin with a viscosity of 2200 cP at the 140 °F processing temperature.

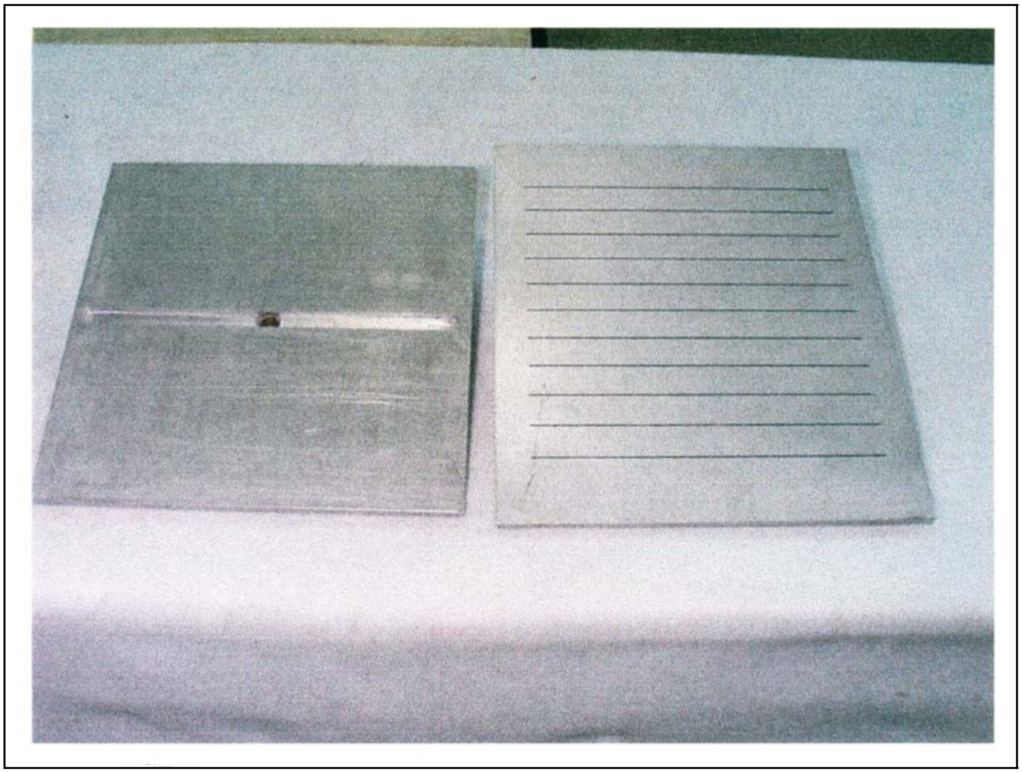

Figure 10. Aluminum processing apparatus used in the second new VARTM process.

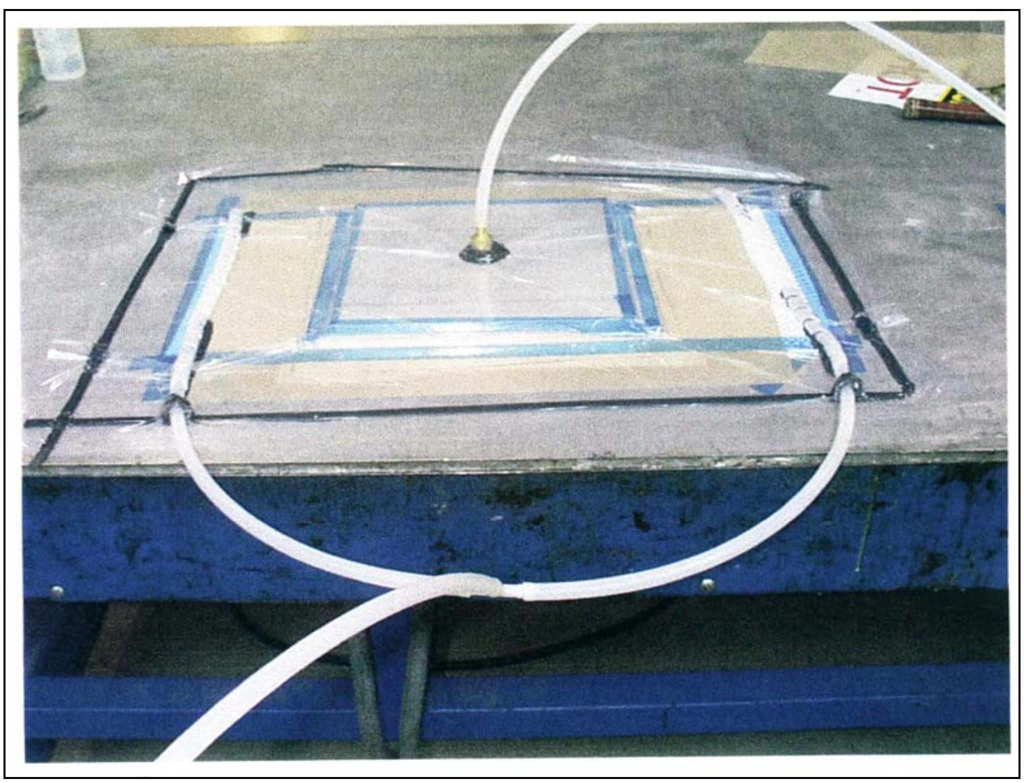

Figure 11. A part ready for resin infusion using the second new process.

The initial processing apparatus was made from aluminum. A modest effort was required to clean this apparatus for reuse. Subsequent processing apparatus for use with hard resins was made from nylon ~0.1 in thick for the two slotted parts. A metal plate with a fill line attachment was then placed over the two nylon parts. This could be twisted easily to remove solidified resin from the slots after processing and the remaining solidified resin could be wiped off with a rag. For processing soft resins such as polyurethanes, the metal apparatus was better; it was possible to grab one end of the cured excess resin and pull it out in one piece, leaving clean apparatus behind.

The process just described was demonstrated on relatively small (typically 1 ft^2) flat plates. Extension of the process to larger parts should be straightforward. Several sets of apparatus could be used that could be infused with resin sequentially if this proved to be necessary. Extension to shaped parts is also possible. Apparatus for infusing a 5-sided box was designed but not tested since the need for the box disappeared. Rounded parts would require appropriately designed tooling, but this tooling could be made.

Fiber volume fractions of 0.58 to 0.60 can be obtained by not completely filling out the edges of the part, as previously indicated. However, a better method is to add some spacers under the outermost plate and then clamp the top and bottom plates together using C-clamps. For low fiber volume fractions, this process reproduces Vmin results. It also allows for fiber volume fractions as high as 0.60 using only atmospheric pressure. Although the spacers are not strictly necessary for high fiber volume fractions, they do make it easier to clamp the part uniformly.

One advantage to having the part clamped in this manner is that once the part is filled, the process is complete. The vacuum can be turned off and the part allowed to cure in the clamped mold.

Panels made using these processes were used in a study of the microwave dielectric properties of polyester and vinylester matrix glass reinforced composites.[3] Very little sanding was required to obtain the flatness and parallelism for these samples with minimal depth gradient of volume fraction. In contrast, samples made by SCRIMP typically had to have the top 40% to 50% sanded off before consistent dielectric constant measurements were obtained because of the extensive V_f gradients.

High V_f composites could also be made by the Vmin process with appropriate spacers and clamps. The process previously described is faster and possibly easier, however.

[3]Spurgeon, W. A. *Free Space Measurement of the Dielectric Constants of Constants of Some Polyester, Vinyl-Ester and Cyanate-Ester Resins and Their Glass Reinforced Composites*; ARL-TR-3083; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2003.

4. Conclusions

Two new VARTM processes have been described that allow control of the fiber volume fraction, thickness, and uniformity of the composite parts. The processes also meet the other criteria described in the introduction.

Appendix. SCRIMP

Seeman's Composite Resin Infusion Molding Process is shown in figures A-1–A-4. The dry fabrics were first cut to size and laid out on a plate to which mold release has been applied. They were then covered with one or more sheets of a porous release fabric such as the green Richmond A8888 release fabric shown in figure A-1. A layer of transfer medium, such as the 50% shade awing screen also shown in figure A-1, is then placed over the part. The transfer medium was cut ~1 in smaller than the part on the vacuum side. This forced the resin to flow down through the part, thus completely filling the part before the resin reached the vacuum line. The transfer medium was also cut ~0.5 in smaller than the part on the two sides perpendicular to the fill and vacuum lines. This prevented the development of a low impedance path (a "racetrack") along the sides of the part. A fill line, made from stretched 0.5-in ID Panduit plastic electrical wrapping (part number T62F) or from a stretched metal spring and covered with several layers of the transfer medium, is placed adjacent to the part. A vacuum line, made from the spiral wrapping or metal spring covered with several layers of 8.8 oz was placed ~6 in away from the other side of the part on a piece of scrap glass fabric that abutted the part (figure A-2). Figure A-3 shows a sketch of the layers of material as viewed from the side. The entire assembly was then vacuum bagged as shown in figure A-4 using a thin plastic bagging material such as 0.002-in thick CAPRAN.[*] The part was then infused with resin. After the resin cured, the part was debagged and trimmed tom size.

As an example of the types of problems that can occur with this process, a multilaminate panel was fabricated using 20 plies of type 6781 S-2 glass, with every fourth ply separated by an 0.003-in thick piece of porous glass coated Teflon release fabric. Each ply of glass fabric was 6 in wide × 30 in long. The part was infused with resin as described previously. The sample was cured and dissected. Thickness measurements were made at five locations along each 4-ply laminate. The results are presented in table A-1. Both through the thickness and end to end gradients are evident.

Table A-1. Thickness measurements in mils for the multilaminate panel.

Position	Laminate 1 (bottom)	Laminate 2	Laminate 3 (center)	Laminate 4	Laminate 5 (top)
1 (fill)	48	48	49	49	50
2	45	45	46	47	49
3 (center)	43	43	44	45	45
4	42	43	43	45	46
5 (vacuum)	41	42	42	44	46

[*]Northern Fiberglass Sales, Inc., P.O. Box 2010, Hampton, NH 03843-0598.

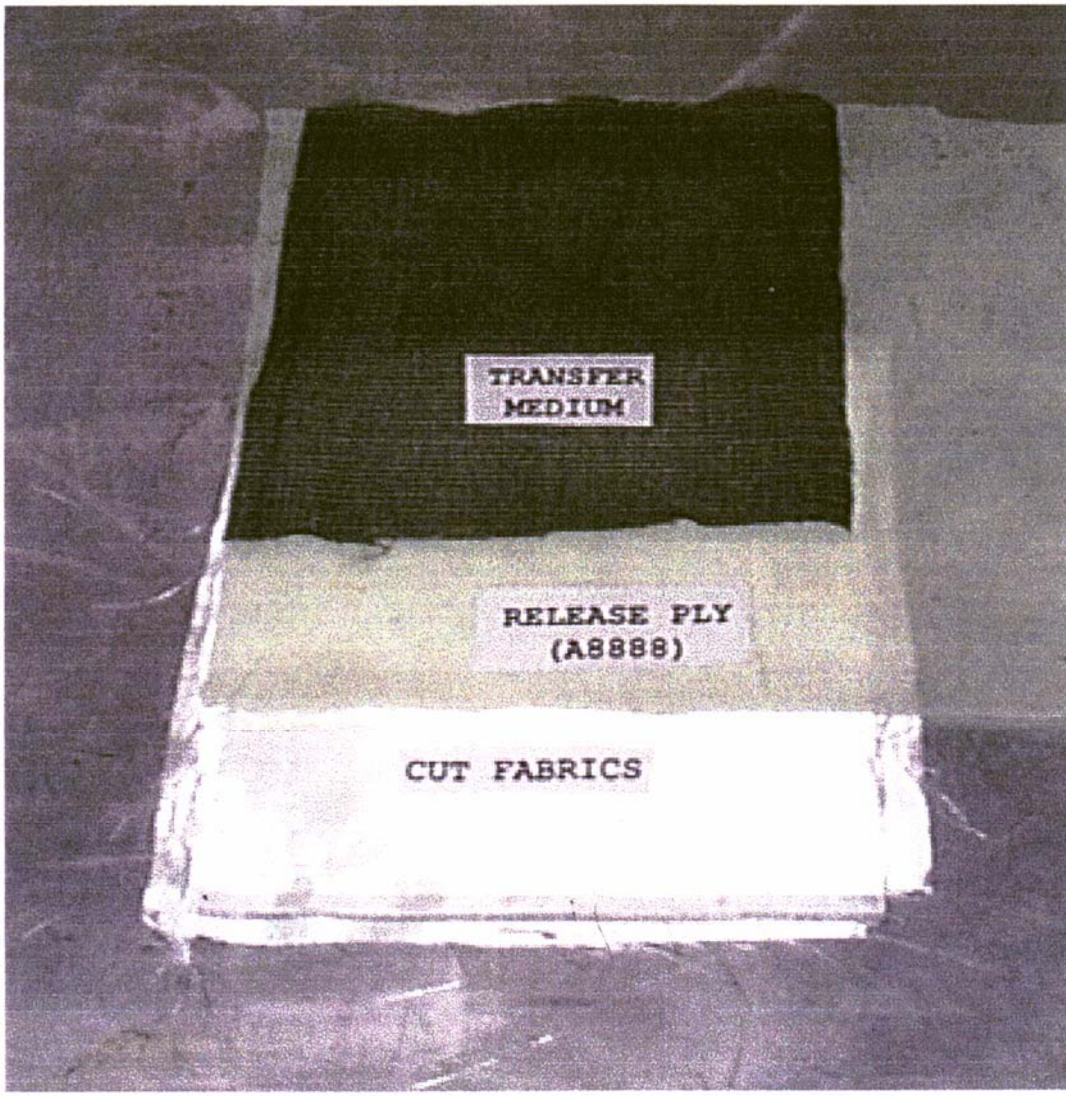

Figure A-1. The cut fabrics are covered with a porous release fabric (green material) and a transfer medium (black material).

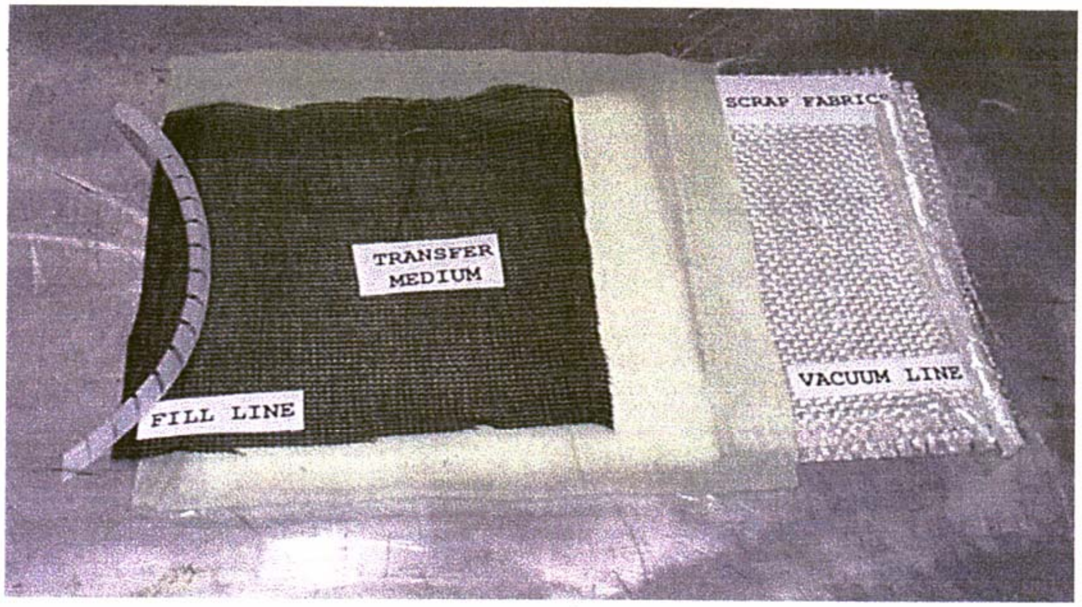

Figure A-2. A fill line (left) is placed next to the part, and a vacuum line (right) is placed several inches away on a thin (50 mil) layer of scrap fabric that abuts the part.

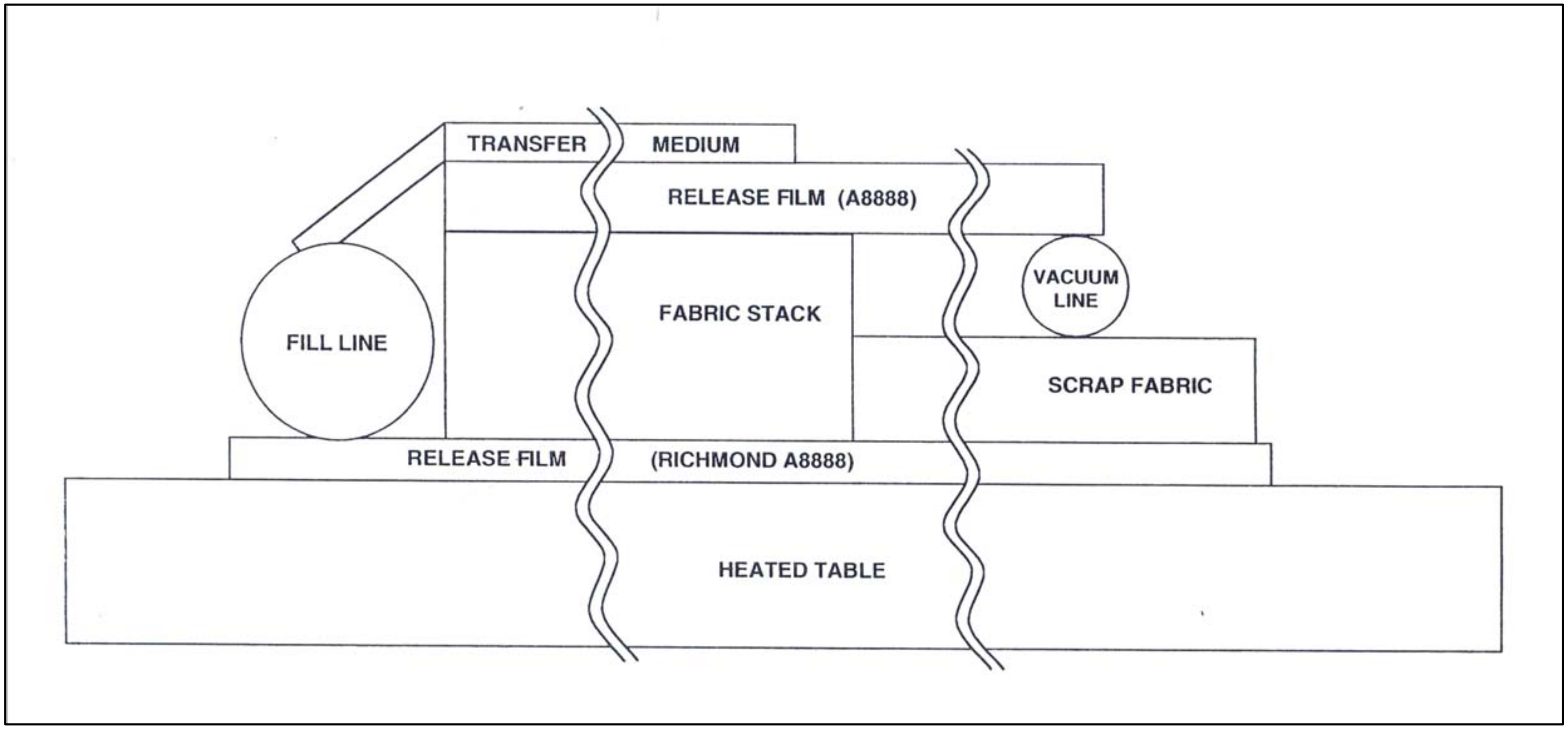

Figure A-3. A sketch showing the layers of material viewed from the side.

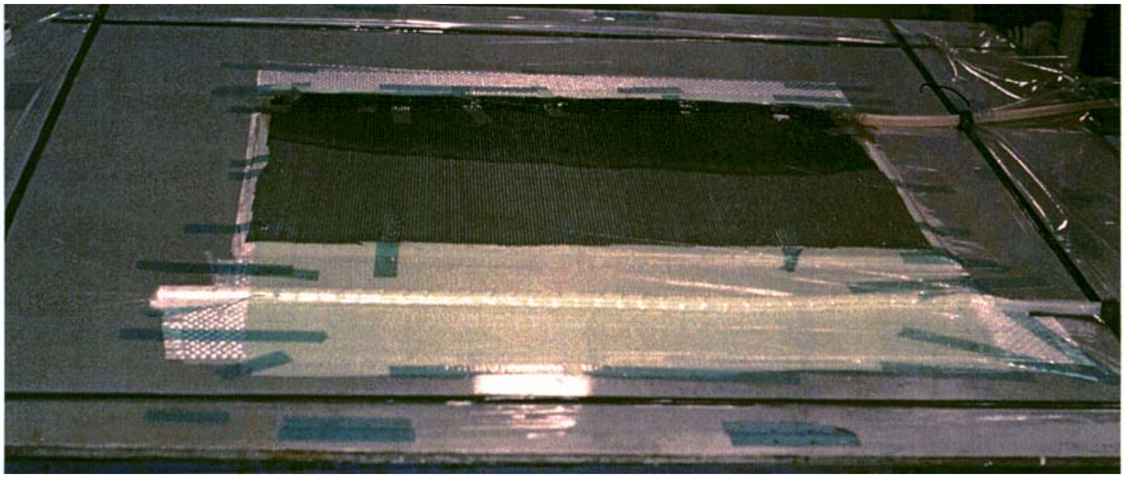

Figure A-4. The assembly is then vacuum bagged and infused with resin.

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